EVALUATION OF KNOCK BEGIN IN SPARK-IGNITION ENGINES BY LEAST-SQUARES

Mark Urlaub and Johann F. Böhme

Department of Electrical Engineering and Information Science,
Ruhr-Universität Bochum, 44780 Bochum, Germany
url@sth.rub.de

ABSTRACT

In order to detect knock in spark ignition engines, usually structure-borne sound signals measured by acceleration sensors mounted on the engine housing are analyzed. However, the sound signal is distorted and disturbed, whereas expensive measuring of the in-cylinder pressure signal provides best information of combustions.
Based on a vibration signal model, a least-squares method is applied to estimate the model parameters from structure-borne sound. Afterwards the estimated parameters can be used in an appendant in-cylinder pressure model for pressure approximation. For a good approximation of pressure signals it is essential to estimate accurately the starting time of knock, which is incapable of measurement. In this paper a theoretical evaluation of the estimated knock begin is provided. Additionally, a reference for the knock begin, based on the pressure model, is derived, such that an evaluation can be given for measured data.

1. INTRODUCTION

Increasing environmental awareness, tightened laws, and last but not least ascending fuel prices push the motor industry to develop more and more efficient internal combustion engines exhausting less pollutants. An important approach is the optimization of the combustion process. Due to thermodynamic reasons engine efficiency depends on compression ratio; the higher the ratio, the higher the efficiency. Unfortunately, compression ratio is limited by the appearance of knock. Knock is an undesired spontaneous auto-ignition of the unburnt air-gas mixture causing a rapid increase of pressure and temperature. Generally, rare knock has no effect on engine performance, but frequent or intense knock can damage the engine and increase pollution. The efficiency of most modern engines reaches its optimum in working conditions with respect of ignition and injection timing where knock can appear. Therefore knock detection is an important task to enable engine management to adjust parameters optimally.

The rapid pressure increase excites resonances with combustion chamber and temperature dependant frequencies [1]. Special pressure sensors mounted in the cylinder head or in the spark plug can be used to measure the excitation of the resonances; but this method is expensive and complex. Therefore the measuring of the in-cylinder pressure is not suitable for serial product engines.

In recent cars acceleration sensors mounted on the engine housing measuring the structure-borne sound as a distorted version of the pressure signal are used. A common method for knock detection in serial cars is to estimate the energy in a relatively wide band of the structure-borne sound signal and compare it to a certain threshold [2]. However, the vibration signals are disturbed by mechanical noises e.g. valve noise, increasing the signal-to-noise ratio. It was shown in [3] that the pressure signal can be approximated from structure-borne sound with appropriate signal models, considering e.g. a random starting time of knock. For best approximation the unknown knock begin has to be estimated accurately. In this paper the estimation of random knock begin is evaluated by simulated data. In order to evaluate the estimation method in applications, an appropriate reference, based on the pressure model, is derived and compared to the estimated knock begin from real data.

This paper is structured as follows. Section 2 presents signal models for pressure and structure-borne sound. In section 3 a reference for the knock begin is derived. Section 4 shows some simulation results while section 5 gives an evaluation for measured data. Finally, the paper concludes with section 6.

2. SIGNAL MODELS

It is well known that knock excites combustion chamber and temperature dependant resonances, which can be computed by finite element method (FEM) for known engine geometries [4]. Figure 1 shows a characteristic highpass filtered pressure signal of a knocking combustion. The excited resonances can be identified in figure 2, where the Wigner-Ville spectrum of several knock signals is given. As in [3] we model the highpass filtered pressure signal within a crank angle interval of 0° and 90° with respect to the top dead

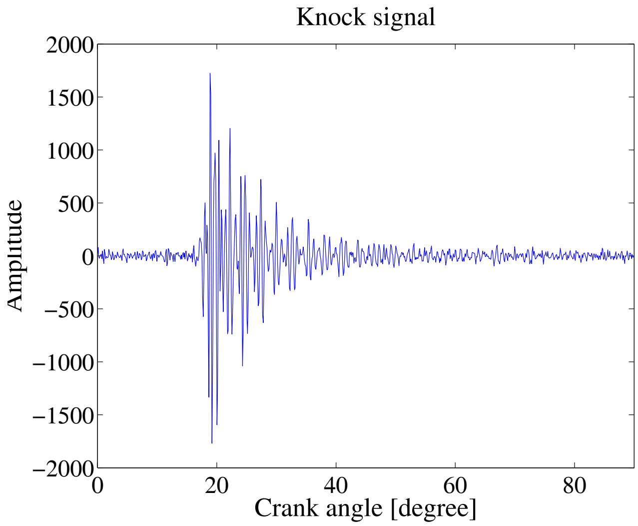

Fig. 1. Characteristical highpass filtered pressure signal suffered by knock

center (TDC) of the according cylinder as

$$x_n^+ = \sum_{p=1}^{P} A_p w_{p,n-n_0} e^{j\varphi_{p,n-n_0}} + z_n \quad 1 \leq n \leq N \quad (1)$$

$$= \sum_{p=1}^{P} a_p m_{p,n-n_0} + z_n \quad (2)$$

with

$$\varphi_{p,n} = \tilde{\varphi}_{p,n} + \phi_p. \quad (3)$$

Thus the analytical pressure model in (1) is a disturbed superimposition of P resonances, where the damped and oscillating behavior of the signals is described by an amplitude modulation $w_{p,n}$ and a phase term $\varphi_{p,n}$. Additionally, the phase (3) is characterized by its instantaneous frequency $\dot{\tilde{\varphi}}_{p,n} = 2\pi f_{p,n}$ and a random initial phase ϕ_p, whereas the random parameter A_p is a measure for the intensity of the p-th resonance. The random starting time of knock is denoted by n_0. For a more convenient notation of (1) the random parameters A_p, ϕ_p are combined in a complex amplitude $a_p = A_p e^{j\phi_p}$ whereas the amplitude modulation and the phase are described by a resonance pattern function $m_{p,n} = w_{p,n} e^{j\tilde{\varphi}_{p,n}}$.

The structure-borne sound can be described as a linear time-variant filtered version of the pressure signal, where the time-variant characteristic results from the moving piston. Due to its motion the area of the combustion chamber wall, where the pressure signal is injected in the engine block, varies. In order to consider this behavior, we model the transmission through the engine block by a linear, time-variant impulse response $h_{n,m}$ as in [3], so that the model

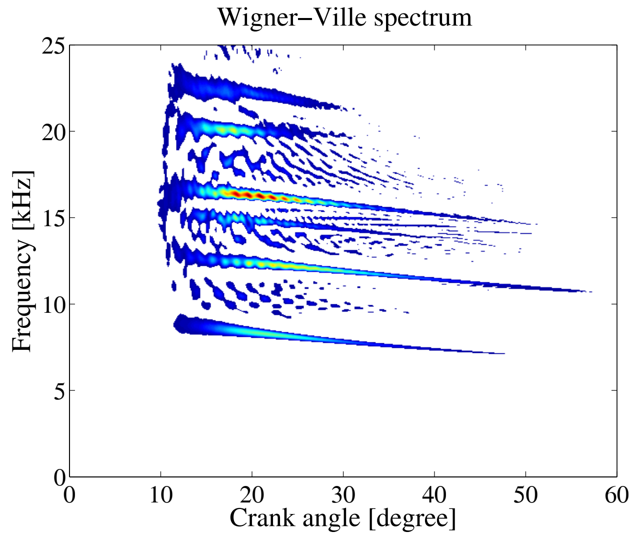

Fig. 2. Wigner-Ville spectrum of several knock signals

for the structure-borne sound yields to

$$y_n^+ = \sum_{m=m_1}^{m_2} h_{n,m} x_{n-m}^+ + v_n, \quad (4)$$

where v_n is additional noise and $m_2 - m_1 + 1$ denotes the filter length. In fact, m_1 should be 0 due to the causal system, but we got better results for small negative values of the non-causal parameter m_1.

Once $w_{p,n}$, $\tilde{\varphi}_{p,n}$ and $h_{n,m}$ are known, the random parameters A_p, ϕ_p and n_0 can be estimated by least-squares [3]. Examples how the amplitude modulation, the instantaneous frequency as well as the impulse response can be determined are given in [3, 5].

3. KNOCK BEGIN REFERENCE

Since the starting time of knock is incapable of measurement, a reference for n_0 has to be found. Generally, the pressure signal provides best information about the combustion process, so that the pressure model is the key for deriving an appropriate reference of the knock begin. Equation (2) can also be stated in matrix notation as

$$\underline{x}^+ = \mathbf{M}_{n_0}^H \underline{a} + \underline{w} \quad (5)$$

with amplitude vector $\underline{a} = (a_1 \dots a_P)'$ and resonance pattern matrix $\mathbf{M}_{n_0} = (\underline{m}_{1,n_0} \dots \underline{m}_{P,n_0})^H$, where $\underline{m}_{p,n_0} = (m_{p,1-n_0}, \dots, m_{p,N-n_0})'$.
Assuming a fixed n_0, the least-squares estimation for the complex amplitude and the mean square error is given by

$$\hat{\underline{a}}(n_0) = (\mathbf{M}_{n_0}\mathbf{M}_{n_0}^H)^{-1}\mathbf{M}_{n_0}\underline{x}^+ \quad (6)$$

$$MSE(n_0) = |\underline{x}^+|^2 - \underline{x}^{+H}\mathbf{M}_{n_0}^H(\mathbf{M}_{n_0}\mathbf{M}_{n_0}^H)^{-1}\mathbf{M}_{n_0}\underline{x}^+. \quad (7)$$

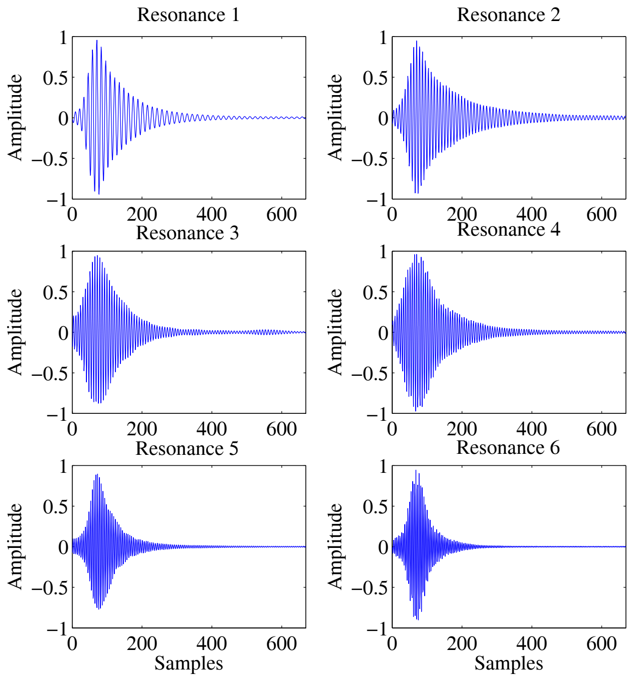

Fig. 3. Pressure pattern functions

After $\underline{a}$ and especially the MSE are known for a certain knock begin, equation (7) has to be minimized regarding n_0, which results in a maximization of its second term. More detailed,

$$\hat{n}_0 = \arg\max_{n_0} |\rho_{\underline{x}^+\mathbf{M}}(n_0)|^2 \tag{8}$$

where

$$|\rho_{\underline{x}^+\mathbf{M}}(n_0)|^2 = \frac{\underline{x}^{+H}\mathbf{M}_{n_0}^H(\mathbf{M}_{n_0}\mathbf{M}_{n_0}^H)^{-1}\mathbf{M}_{n_0}\underline{x}^+}{|\underline{x}^+|^2} \tag{9}$$

is a squared correlation function between measured pressure signal and pressure pattern functions. The result in equation (9) is similar to the estimation of n_0 from structure-borne sound in [3], wherein $|\rho_{\underline{y}^+\mathbf{N}}(n_0)|^2$, the squared correlation function between measured structure-borne sound $\underline{y}^+$ and vibration pattern function $\mathbf{N}_{n_0}^H$, has to be maximized.

4. SIMULATION

The simulated data is based on the pressure model in (1). First, the amplitude modulation and instantaneous frequency, which are engine specific and already determined in [3] for an 1.8l VW-Passat engine, are applied to the pressure model. Figure 3 shows the resulting pressure pattern functions $\underline{m}_{p,n_0}$, $1 \leq p \leq P$, assuming $P = 6$ resonances for 1750 rpm. Parameters A_p, ϕ_p as well as n_0 are randomly generated with a uniform distribution, for $0 < A_p < 1000$, $0 < \phi_p < 2\pi$ and $0° < n_0 < 20°$ crank angle. The

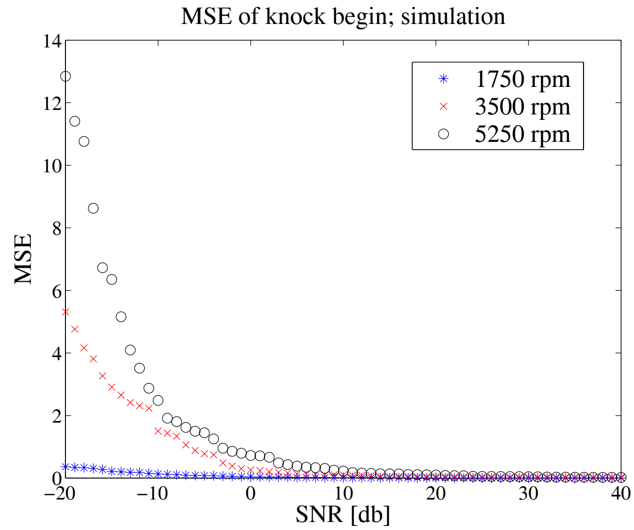

Fig. 4. MSE of knock begin for simulated data

structure-borne sound pattern functions are obtained by linear time-variant filtering of pressure pattern functions using the estimated impulse response for $m_1 = -29$, $m_2 = 100$ from [3]. Finally, the synthetic signals are disturbed by gaussian noise for different signal-to-noise ratios (SNR), $-20\text{db} < \text{SNR} < 40\text{db}$.

Figure 4 shows the mean square error (MSE) over signal-to-noise ratio for three speeds: 1750 rpm, 3500 rpm, 5250 rpm. With increasing SNR the MSE decreases as it was expected. The results for 1750 rpm provides the lowest mean square error. With increasing speed the results for lower SNR become worse. However, for SNR $>$ 0db the experiments are still satisfying as for knock signals a higher signal-to-noise ration can be expected.

5. EXPERIMENTAL RESULTS

The experiments analyze the pressure and sound signals of an 1.8l VW-Passat engine for 1750 rpm, 3500 rpm and 5250 rpm regarding the knock begin n_0. The data set contains knocking combustions as well as non-knocking or weakly knocking combustions, respectively. In order to determine the reference from pressure signals, the pressure pattern functions $\underline{m}_{p,n_0}$ of figure 3 are applied to (9) for 1750 rpm. Similar pattern functions for other speeds are equivalently determined as for 1750 rpm. The estimated knock begin from structure-borne sound is the maximum of the squared correlation function between the analytical vibration signal and the vibration pattern function, similar to equation (9) as it was derived in [3].

Figure 5 shows the correlation between estimated knock begin and the according reference for different speeds. For 1750 rpm the estimation of n_0 is successful as most of the

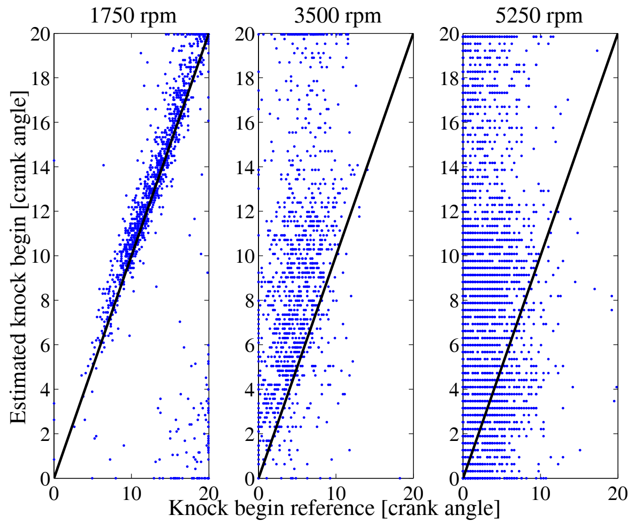

Fig. 5. Correlation between reference and estimation of knock begin for different speeds

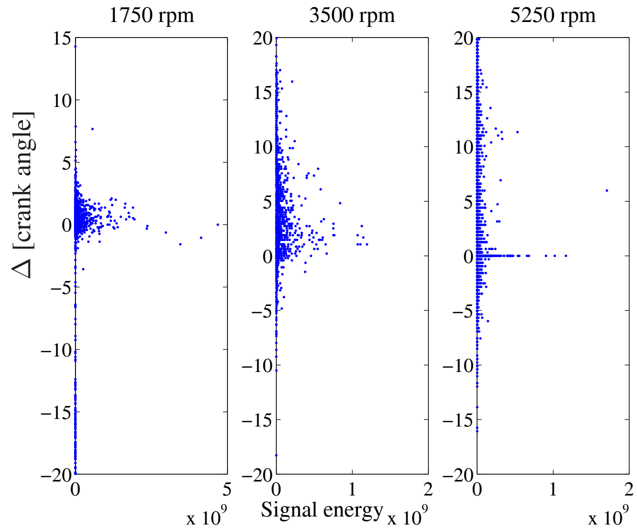

Fig. 6. Difference Δ between reference and estimation of knock begin regarding signal energy for different speeds

correlations are close to the optimum line. For 3500 rpm the knock begin is slightly overestimated, which means a greater estimated n_0 than the reference; but the results are still satisfying. For 5250 rpm the estimation fails. As section 4 showed, the performance of knock begin estimation for lower speed is promising. But with increasing speed the estimation fails.

Figure 6 shows the difference Δ between estimated knock begin and its reference over signal energy. As expected the variance for 1750 rpm is smaller than for 3500 and 5250 rpm. But even for higher speeds the difference between reference and estimated n_0 is still small for increasing signal energy. Obviously, for strongly knocking combustions the estimation of the starting time of knock is promising. Additonally, taking a closer look at the signal energy, the maximum of the signal energy at 1750 rpm is higher than at other speeds. This could be a reason for a better estimated n_0 at low speeds.

6. CONCLUSION

It was demonstrated that the starting time of knock, which is essential for pressure approximation from structure-borne sound and is incapable of measurement, can be estimated with appropriate signal models. In simulations the performance of the estimated knock begin dependant on signal-to-noise ratio was evaluated. For lower speeds the simulations were promising, whereas for increasing speed the estimation quality decreases. Finally, the algorithm was applied to measured data. The results approved the evaluation for simulated data; but, an accurate estimation of n_0 for higher speeds can still be performed assuming strong knocking combustions. Hence, the model concidering a random knock begin should be adequate for knock detection.

7. REFERENCES

[1] R. Hickling, D.A. Feldmaier, F.H.K. Chen, J.S. Morel, "Cavity resonances in engine combustion chambers and some applications," *J. Acoust. Soc. Am.*, vol. 73 (4), pp. 1170-1178, 1983.

[2] O. Boubal,"Knock detection in automobile engines,", *IEEE Instrumentation and Measurement Magazine*, vol. 3, pp. 24-28, Sep. 2000

[3] M. Urlaub, J.F. Böhme, "Reconstruction of pressure signals on structure-borne sound for knock investigations," *SAE 2004 World Congress & Exhibition*, SAE technical paper 2004-01-0521, Mar. 2004

[4] S. Carstens-Behrens, M. Urlaub, J.F. Böhme, J.F. Förster, J. Raichle, "FEM Approximation of Internal Combustion Chambers of Knock Investigation", *SAE 2002 World Congress & Exhibition*, SAE technical paper 2002-01-0237, Mar. 2002

[5] L. Stanković, J.F. Böhme, "Time-frequency analysis of multiple resonances in combustion engine signals", Signal Processing, vol. 79, no. 1, pp. 15-28, Nov. 1999